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NEUTRON STARS

INGRID H. STAIRS[1†], CHRISTOPHER THOMPSON[2†], JEREMY HEYL[1], NATASHA IVANOVA[3], VICTORIA M. KASPI[4], RACHID OUYED[5], HARALD PFEIFFER[2], SAMAR SAFI-HARB[6], MARTEN VAN KERKWIJK[7]

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ABSTRACT

Neutron stars provide insight into the structure of matter at extreme densities, the validity of gravitational theories near strongly self-gravitating objects, and QED phenomena in high magnetic fields. Observations and theory also shed light on supernova mechanisms, properties of supernova remnants and dynamical interactions in globular clusters. Future progress in these areas will require the Square Kilometre Array to provide good sensitivity at radio wavelengths. The International X-ray Observatory is the major long-term complement to SKA in the X-ray band. Access to strong high-performance computing will be equally essential, to enable theoretical calculations and to handle large observational data volumes.

1. INTRODUCTION

Neutron stars (NSs) are observed from the radio to gamma ray bands, with valuable science gleaned from all wavelengths. One of the powerful techniques employed is phase-coherent timing of pulsed NS emission seen at radio, X-ray and/or gamma-ray wavelengths, accounting for each rotation of the pulsar and allowing ultrahigh precision measurement of spin, astrometric and orbital parameters. Large telescope collecting areas are required in order to build up good signal-to-noise ratios on timescales short compared to the phenomena being measured. Searches for new pulsars use Fourier techniques to find periodicities in deep data sets, and allow for the dispersive effects of the interstellar medium (ISM) at radio wavelengths by searching over the electron column density or "dispersion measure" (DM). Imaging and astrometry provide information on NS positions and environmental structure at all wavelengths. At optical and X-ray frequencies, spectroscopy, deep and/or resolved by pulse or orbital phase, is important for NS and supernova remnant (SNR) emission and composition modeling and for orbit determination and mass modeling for white-dwarf (WD) or other optical companions. High performance computing is essential for pulsar searches, especially for rare binary objects, and for all sky monitoring of transient NSs.

Neutron stars are also exquisite probes of fundamental physics, especially of the properties of matter much denser than an atomic nucleus, and of ultrastrong gravitational fields. Fundamentally new states of matter may yet be uncovered within them. The magnetic fields that surround them are strong enough to deform atoms and modify the structure of the vacuum. Some radio pulsars are the best clocks in nature, and are sensitive to faint cosmic backgrounds of gravitational radiation. Other NSs release the brightest flashes of X-rays and gamma-rays detected from the cosmos. A small proportion die in intense collisions with other relativistic stars, and represent a leading source of cosmic gamma-ray bursts and the most promising detectable source of gravitational waves. Neutron stars are also formed in dense stellar clusters, and interact with their more ordinary stellar companions in astonishing ways. Some key components of pulsars, such as solid crusts and superfluid neutron vortices, were predicted theoretically long ago, but their dynamics is only beginning to be explored through extreme phenomena such as glitches and magnetar bursts. Pulsars have high speeds of rotation and translation which, together with their intense magnetism, reflect the conditions of their birth in supernova explosions and stellar interactions. Much is still to be learned about the extraordinary diversity of supernovae, and their stellar remnants.

We highlight the contributions of **Canadian** researchers in bold type.

2. NEUTRON STAR STRUCTURE

The equation of state (EoS) of dense matter can be derived from nuclear many-body theory or an effective theory of the strong interaction, but these different approaches have not yet converged on a unique result (Akmal et al. 1998; Wiringa et al. 1995; **Ouyed** & Butler 1999; Jaikumar & **Ouyed** 2006). Valuable experimental benchmarks will be provided in the future by heavy-ion collisions and experimental probes of nuclear matter near saturation density. To give one example, at densities much above saturation, the Ouyed-Butler-Jaikumar EoS is very stiff, consequently yielding the heaviest possible hadronic stars ($> 2M_\odot$).

The measurement of NS masses is one key method to constrain allowed EoS, an area in which Canadian-led discoveries have played a significant role in recent years. Radio pulsars in binary systems can provide masses via timing if at least two relativistic corrections to the Keplerian radial-velocity orbit can be measured (e.g., Splaver et al. 2005). The results range from 1.24 to $1.44\,M_\odot$ for double NS systems (e.g., **Stairs** 2008), and extend up to $1.74\pm0.04\,M_\odot$ for PSR J1903+0327 (**Champion** et al. 2008). Many more candidate sources are continuing to be discovered, especially in globular clusters (Ransom et al. 2005; Freire et al. 2008b).

[1] Department of Physics and Astronomy, 6224 Agricultural Road, University of British Columbia, Vancouver, BC V6T 1Z1
[2] CITA, University of Toronto, 60 St. George Street, Toronto, Ontario, M5S 3H8
[3] Department of Physics, University of Alberta, Edmonton, Alberta T6G 2G7
[4] Department of Physics, McGill University, 3600 University St., Montreal, QC H3A 2T8
[5] Department of Physics and Astronomy, University of Calgary, SB 605, 2500 University Drive NW, Calgary, Alberta, T2N 1N4
[6] Department of Physics and Astronomy, University of Manitoba, Winnipeg, Manitoba, R3T 2N2
[7] Department of Astronomy and Astrophysics, University of Toronto, 60 St. George Street, Toronto, Ontario, M5S 3H8
[†] Editor

Constraints can also be derived from observations of optical companions. Combining the pulsar timing orbit with a radial-velocity orbit, the mass ratio is obtained, usually to very good precision, and only one further property is needed to specify the masses. Two approaches have been used. For WD companions, the spectrum yields the surface gravity, and thus the mass, via the WD mass relation (e.g., van Kerkwijk et al. 1996). For non-degenerate companions that are irradiated or tidally distorted, careful measurement of the light curve yields the inclination (e.g., Reynolds et al. 2007). Astrometry is another useful technique: for example, for PSR J1023+0038, a mass can be obtained by combining a VLBA parallax with the fact that the companion should be filling its Roche lobe, since this binary had an accretion disk not so long ago (**Archibald** et al. 2009). In the future, optical astrometry will allow the spatial resolution of wide companion orbits.

Limits on the EOS can also be derived from NS rotation rates, if these approach the mass shedding limit. Such is not the case for known radio pulsars, but the search for faster rotators continues, and super-kHz spin rates may yet be found in LMXBs, as has been reported during X-ray bursts of XTE J1739-285 (Kaaret et al. 2007).

Combined measurements of mass and radius require more information, e.g. from the spin-orbit interaction, which may be measurable through radio timing in PSR J0737–3039A (Kramer et al. 2006). Precision measurements of the hydrogen spectra of quiescent LMXBs offer another promising approach (**Rutledge** et al. 2002; see also the white paper by Heinke et al.). Measurements of the gravitational radiation emitted during the inspiral and merger of relativistic binaries will also constrain the $M-R$ relation of component NSs. Fitting theoretical templates to data collected by observatories such as Advanced LIGO will provide component masses and spins, a luminosity distance, and result in a rough sky localization. In a NS-black hole merger, the NS may be tidally disrupted or swallowed whole, depending on the mass and spin of the black hole, and the compactness of the NS. Advanced LIGO may see NS-BH mergers at a rate of about 10/yr, and NS-NS mergers at a rate of about 40/yr. In the latter case, it will measure the NS compactness to about 10 percent accuracy (Read et al. 2009).

2.1. *Crustal Composition*

A combination of techniques from materials science, nuclear physics, and condensed matter have recently been brought to bear on the crucial problem of the structure of NS crusts (**Hoffman** & **Heyl** 2009; Horowitz & Berry 2009; **Medin** & **Cumming** 2010). The detailed properties of the crust, and the connectivity of its magnetic field, determine the luminosity from young isolated NSs; without this knowledge it is difficult to translate observations of young NSs into constraints on the high-density interior and its exotic material. The most promising probes of the thermal properties of the crust are the transient LXMBs where the thermal driving of the crust is known and after the accretion ceases the cooling of and through the crust dominates the emission. Recent calculations to simulate the freezing of NS crusts indicate that nuclei are segregated by atomic number between the liquid and solid states (Horowitz et al. 2009). This segregation if verified at smaller concentrations of impurities could dramatically affect our estimates of the thermal conductivity and the rate of magnetic field decay in NS crusts, and the implied surface temperatures.

A complementary probe of the crust is pulsar glitching, which provides good evidence for a crustal neutron superfluid that contributes about a percent of total moment of inertia of the star (Link et al. 1999). The mechanism triggering glitches has not yet been reliably determined, although strong circumstantial evidence suggests that magnetic disturbances are responsible in magnetars (**Kaspi** et al. 2003). Some glitch observations are however ambiguous as to the location of the superfluid component, and it is possible that the core superfluid is involved in some cases (**Dib** et al. 2008; **Livingstone** et al. 2010). Deep spectroscopy in the soft X-ray band (e.g. with IXO) will be essential to unraveling these effects.

3. DIVERSITY

Although radio pulsars were the first recognized manifestation of NSs, the four decades since their discovery have led to the realization that there are in fact several different classes, with interrelationships that are slowly becoming clearer. One new class of NS emits only occasional radio pulses (RRATs; McLaughlin et al. 2006), meaning that the overall NS population must be much larger than previously thought. Young pulsars with very strong (e.g. Camilo et al. 2000) and weak (e.g. Halpern & Gotthelf 2010) magnetic fields are increasingly being found, and demonstrating that the classical examples of the Crab and Vela pulsars are not necessarily typical. Meanwhile the high-energy properties of pulsars are being made clear by satellites such as Fermi, with many pulsars shown to be gamma-ray emitters (Abdo et al. 2009) and with Fermi point sources proving to be excellent signposts to millisecond pulsars (Ransom et al. 2010).

Other discoveries reflect increasing diversity in the population of NS binaries: a most unusual Galactic Plane millisecond pulsar is paired with a massive companion in an eccentric orbit, puzzling to binary evolution theorists (**Champion** et al. 2008), while on the other hand PSR J1023+0038 lends support to the standard recycling picture by being a millisecond pulsar whose companion has not yet made the transition to a WD (**Archibald** et al. 2009). Pulsar population modeling (e.g., **Faucher-Giguère** & **Kaspi** 2006) is a burgeoning field of study, and the large-scale surveys underway at major radio telescopes and anticipated with the SKA and its pathfinders will provide new statistics for these purposes and very likely entirely new classes of objects.

3.1. *Magnetars*

The last decade saw convincing evidence for a dramatic proposal from the mid-nineties, that some NSs have magnetic fields so strong that the decay of the field dominates the radiative emissions of the star. In the most extreme cases, magnetic stresses within a magnetar appear to cause sudden ruptures of its rigid crust, which are seen as bright flashes of X-rays and gamma-rays (Soft Gamma Repeater bursts). Magnetars in quiescence are bright, but relatively soft, pulsing X-ray sources. The basic theory of magnetar bursting and quiescent emission was developed in Canada (**Thompson** & Duncan 1995, 1996; **Thompson** et al. 2002). Kaspi's group has provided key insights through the application of pulsar timing techniques, which have revealed large variations in X-ray flux and spindown torque even in relatively quiescent states (**Kaspi** et al. 2001; **Gavriil** & **Kaspi** 2002; **Kaspi** et al. 2003). The expectation that quiescent magnetars would eventually emit bright X-ray bursts has also received dramatic confirmation (**Gavriil** et al. 2002). The variability of magnetars is broadband, extending from the X-ray through the infrared, and into the radio in some cases.

Population modeling indicates that magnetars make up at least $\sim 10\%$ of the Galactic NS population (e.g. **Gill** & **Heyl** 2007). One interesting open question is the extent to which strong-field objects detected through non-thermal pulsar-like emissions represent transition objects between magnetars and the bulk of the radio pulsar population, or could even evince classical magnetar behavior for brief intervals (**Kumar** & **Safi-Harb** 2008; Gavriil et al. 2008).

3.2. *CCOs and DINs*

About a decade ago, searches to identify NS by their cooling emission found two new classes of NS: the young "compact central objects" (CCOs) in SNRs, and the middle-aged "isolated NSs" (INS) in the field. Both posed physical and astronomical puzzles in terms of their spectra and their places in the larger population. The last decade has seen at least partial and interesting resolutions to the latter question. Some CCOs appear to have been born with slower spin rates (100s of ms) and lower magnetic field strengths ($\lesssim 10^{11}$ G) than normal pulsars (e.g., Halpern & Gotthelf 2010). Indeed there is growing class of weak-field NSs discovered in the X-ray band which should be long-lived radio sources.

The INS, by contrast, have longer periods (3–12 s) and stronger fields (few $\times 10^{13}$ G), which can most easily be understood if they are heated internally by a decaying magnetic field, and/or are the descendants of NSs with even stronger initial fields (Kaplan & **van Kerkwijk** 2009). Thus, these discoveries linked the various guises in which NSs are found to one parameter, magnetic field strength. One consequence of these discoveries is that the total NS population was at least double that inferred earlier from just radio pulsars and magnetars (**Gill** & **Heyl** 2007).

The CCO spectra are puzzling in that fits with black body or hydrogen atmosphere models yield radii that are too small for a NS. A possible solution, found only recently for the CCO in Cas A, is that the atmosphere is composed of carbon (Ho & **Heinke** 2009). This greatly affects the spectral energy distribution, and leads to the inference of more reasonable radii. The INS spectra, on the other hand, are still mysterious. They look like blackbodies at X-ray wavelengths, but with strong absorption features at energies of 100s of eV, and with a large optical excess. Future work on these puzzles will require both better modeling and high-sensitivity X-ray instrumentation such as IXO.

Finally, while we are obtaining a much better sense of NS variety, a remaining mystery is that many SNRs remain empty, without any obvious compact object. Could those host NSs that cooled much faster? Or possibly low-mass black holes? The latter are expected to form for some EOS, once a massive proto-NS loses pressure support.

Answers may come from observations of core collapse supernovae by neutrino telescopes such as SNO, and from more sensitive radio and X-ray surveys of SNRs. This can partly be done with XMM, Chandra, and existing radio telescopes for the most energetic extragalactic pulsar wind nebulae (PWNe). Much more information will be available from transient surveys like PTF, Pan-STARRS, and eventually LSST and EXIST. A much broader range of newly formed pulsars will be accessible to IXO and SKA.

4. FORMATION AND ENVIRONMENTS

4.1. *Core Collapse Explosions and Neutron Star Formation*

A newborn NS is a promising site for the generation of ultrastrong magnetic fields, given the huge amounts of energy available in differential rotation and convection both inside and outside the neutrinosphere. Although successful supernova explosions have not yet been obtained with confidence in computer simulations, strong clues have emerged to some of the observed properties of pulsars (large kicks and rapid rotation) through instabilities of the shock wave (**Thompson** 2000; Blondin et al. 2003; Scheck et al. 2004). In particular, the origin of rotation through the accretion of $\sim 0.1 M_\odot$ of rapidly rotating material at the tail end of the proto-NS phase would make the relatively high incidence of magnetars easier to understand. Answers to these questions require full three-dimensional collapse simulations, which are now being pursued. The accurate representation of hydrodynamic instabilities in three dimensions depends on high spatial resolution, which will be obtained only gradually over the next decade. Polarimeric observations of supernova explosions are especially useful in constraining the ejecta asymmetry. An astonishing diversity of rare types of energetic and asymmetric explosions is now emerging from transient searches.

4.2. *Supernova Remnants and Pulsar Wind Nebulae*

The birth properties of NSs are probed by observations of young objects still inside natal SNRs. In addition, SNRs and PWNe offer nearby astrophysical laboratories for tracking the heavy elements created in the Universe, probing the interaction between relativistic outflows and the ISM, studying shock acceleration and the origin of high-energy cosmic rays, and unveiling the physics of the extreme associated with NSs and black holes. Furthermore, PWNe serve as calorimeters for the study of their powering engines as well as pathfinders for discovering pulsars which have been otherwise missed with radio or X-ray surveys. More direct constraints on NS birth are being pursued with increasing vigor through observations of extragalactic supernovae. The origin of magnetars in particular may be probed through energy deposition in the surrounding SNR.

In addition to the question of missing compact objects in SNRs (Section 3.2), there are several outstanding problems that should see progress in the coming years. One is our incomplete sampling of young SNRs. It is likely many Galactic events are missed in the optical due to extinction. Radio Canadian Galactic Plane Survey observations and follow-up X-ray observations are unveiling new SNRs and PWNe (e.g. **Kothes** et al. 2006; **Jackson** et al. 2008; Arzoumanian et al. 2008). Pointed hard X-ray telescopes with high sensitivity (such as NuSTAR and Astro-H) have great promise in filling in the gap, and will be able to map out the emission from short-lived radioactive nuclei (especially ^{44}Ti). TeV gamma-ray telescopes such as HESS and Veritas have already made some impressive detections (e.g. Acciari et al. 2009).

Observations of the distribution of nucleosynthetic yields in SNR are still somewhat patchy, but microcalorimeter arrays show great promise in improving sensitivity to X-ray lines in the 3-10 keV band. The magnetic field structure in SNRs is generally poorly understood, but is thought to relate to the diversity in PWNe. While radio polarization studies have been fruitful in shedding light on the magnetic field geometry in some PWNe (e.g. **Kothes** et al. 2008), such studies are often hampered by Faraday rotation and depolarization effects. X-ray polarization offers a new and independent venue to probe the magnetic field structure in SNRs. Finally, the question of ion acceleration in SNRs as a contribution to the observed cosmic ray spectrum up to 3000 TeV can be partially addressed by Fermi in the GeV energy range, but the next generation of hard X-ray and TeV instruments will be needed to increase the sample of TeV emitting SNRs, and will allow a better correlation with X-ray maps, needed to differentiate between the hadronic and leptonic CR models.

4.3. *Globular Clusters*

Globular Clusters (GCs) are another environment which harbour NS in abundance. In the last decade numerous millisecond pulsars have been discovered in GCs, increasing the sample to 140 pulsars in 26 globular clusters. The Canadian community contributed strongly to the discovery of a dozen of new pulsars with Arecibo (**Hessels** et al. 2007), about 40 with GBT (Ransom et al. 2005; Freire et al. 2008b), characterization of a pulsar in a triple system (Sigurdsson et al. 2003), the fastest spinning pulsar to date (**Hessels** et al. 2007), a possibly massive NS (Freire et al. 2008b), and identifying the companions for several pulsars (e.g., van Kerkwijk et al. 2000). Pooley et al. (2003) showed that there is a connection between the number of detected low-mass-X-ray binaries and Γ (the average efficiency of the dynamical encounters). The link between Γ, low-mass X-ray binaries and millisecond pulsar formation helped to make more successful the selection of potentially pulsar-rich clusters and will help with the future searches. The impressive new statistics of radio pulsars permitted further interpretation of NS populations in GCs and lead to the suggestion that electron capture supernova NS formation is especially important in the case of GCs (**Ivanova** et al. 2008a,b), although it likely also plays a role in the formation of some Galactic double-NS systems (e.g., **Stairs** et al. 2006). A further conclusion is that ultra-compact X-ray binaries likely do not lead to the formation of radio pulsars (**Ivanova** et al. 2008b).

Some top achievable goals include understanding how the observed metallicity dependence for X-ray binaries affects the radio pulsar population, understanding the selection effects against binary pulsars in globular clusters, and determining further orbits and companion masses for millisecond pulsars in order to constrain the dynamical formation channels.

5. EXTREME PHYSICS AND GRAVITY

Pulsars are renowned as laboratories for gravitational physics, with Nobel-prize recognition for the discovery of the first double-NS system (Hulse & Taylor 1975). The recently discovered double-pulsar system already surpasses the Hulse-Taylor pulsar in terms of the precision of the gravitational tests, showing agreement of the most precisely measured relativistic parameters and the mass ratio with the predictions of general relativity to 0.05% (Kramer et al. 2006). This system moreover allows the first precision test of the rate of geodetic precession of a pulsar's spin axis (**Breton** et al. 2008), by detailed fitting of the radio eclipse of the faster pulsar to a simple model involving plasma trapped inside a rotating magnetic dipole (**Lyutikov** & **Thompson** 2005). With the SKA and the discovery of suitable systems, pulsar timing could lead to the measurement of the spins and quadrupole moments of black holes (Kramer et al. 2004).

Another project that holds great promise is the use of an array of millisecond pulsars across the sky to constrain or even detect gravitational waves passing near the Earth, likely in the form of a stochastic background. Pulsar groups around the world are working to increase their timing sensitivity and identify and reduce systematics in hopes of reaching the fiducial level of 100 ns rms timing precision on a few tens of pulsars. The Canadian groups are members of the North American "NANOGrav" consortium, which conducts long-term timing with Arecibo and the GBT and which has data-sharing agreements in place with counterparts in Australia and Europe. The pulsar observations are complementary to the LIGO and potential LISA detectors, and the world gravitational wave community has in the last few years come to understand the potential of these measurements. The current goal is to achieve a detection before the SKA comes online; the SKA itself could enable science in the form of a spectrum of the waves and detection of individual sources (e.g. Sesana & Vecchio 2010).

5.1. *Magnetic Field Decay and Magnetars*

Magnetars provide valuable probes of NS interiors through several channels. The thermal X-ray emission from magnetar surfaces is a hundred times brighter than that of ordinary pulsars such as Vela, and lies within a narrow range which suggests buffering of the internal temperature by neutrino emission (**Durant** & **van Kerkwijk** 2006), in line with predictions for heating by ultrastrong magnetic fields in non-superfluid NS cores (**Thompson** & Duncan 1996). Other magnetars are more transient and range between the two extremes of X-ray brightness. One focus of future research will be on whether this difference signals a superfluid transition of the core neutrons: the cooling rate rises strongly after such a transition, but it can be delayed significantly by magnetic heating (Arras et al. 2004).

Persistent vibrations are detected from magnetars during giant outbursts (Israel et al. 2005; Strohmayer & Watts 2005), and directly probe the magnetoelastic modes of the star (Duncan 1998). Several properties of the measured quasi-periodic oscillations suggest persistent fracturing of the crust, with the implication that the observed modes are self-excited and provide valuable information about the triggering mechanism of magnetar bursts.

Magnetar variability is a broadband phenomenon, and much is still to be learned from simultaneous monitoring in the X-ray, infrared, and radio. It is also becoming clear that transient magnetic activity is more widespread within the NS population. Deeper all-sky surveys of transient hard X-ray emission (EXIST or WXFT) will provide a much richer sample of NSs for followup monitoring of pulsed X-ray emission (initially with Astrosat and later with larger timing missions such as AXTAR), combined eventually with sensitive optical (TMT) and radio (SKA) monitoring.

5.2. *Self-Consistent Theories of Neutron Star Magnetospheres and Pulsar Winds*

Modeling the electromagnetic emissions and spindown of radio pulsars and magnetars depends on a fundamental understanding of the flow of plasma through the magnetospheric circuit, and the instabilities that this plasma may experience. After a long hiatus (which has, in good part, been the result of computational limitations) the last few years have seen fundamental progress on this problem, which can be expected to extend into the next decade. Realistic force-free models of three-dimensional magnetospheres of radio pulsars (Contopoulos et al. 1999; Spitkovsky 2006) and magnetars (**Thompson** et al. 2002) have been constructed. Self-consistent calculations of electromagnetic cascades are still in their infancy (Beloborodov & **Thompson** 2007; Luo & Melrose 2008; **Medin** & Lai 2010), but significant progress can be expected in the next decade in meshing them with circuit calculations. Fermi measurements of gamma-ray pulsars already have provided strong constraints on the location of the gamma-ray emission zone. The discovery of intermittent radio emission from the RRATs (McLaughlin et al. 2006) and strongly variable radio emission from magnetars (Camilo et al. 2006), highlights the potential importance of magnetic field variability in triggering coherent radio emission.

Magnetars in particular offer a dramatic test of how NS magnetic fields respond to strong deformations. It is now abundantly clear that the classical approach to pulsar electrodynamics fails to describe the most basic properties of magnetar persistent emission and spindown behavior. A twisting up of the external magnetic field by subsurface instabilities can explain the large variations that are seen in spindown torque; as well as the strong non-thermal emission seen in the 1-10 keV band through multiple cyclotron scattering of thermal X-rays (**Lyutikov** & **Gavriil** 2006; **Fernández** & **Thompson** 2007).

5.3. *Polarization Effects*

Measurements of the polarization of an electromagnetic signal from a NS provides essential information about the geometry of the magnetic field, as has long been familiar from radio studies (Radhakrishnan & Cooke 1969). Even the thermal X-ray emission from the surface of a quiescent NS will be strongly polarized due to the birefringence induced by the magnetic field, combined with polarization mode tracking into the outer magnetosphere (Lloyd et al. 2003; Heyl et al. 2003). Distinct polarization features are expected in the optical to soft-X-ray bands due to a competition between the dispersive effects of the QED vacuum and the embedded plasma (Lai & Ho 2003; **Shannon** & **Heyl** 2006). The most promising sources to measure this effect and provide a direct estimate of the surface fields are the DINS, whose X-ray emission comes predominantly from the surface.

Magnetars are relatively bright sources and good targets for polarimetry. In fact, polarimetric observations are essential to unraveling how magnetic disturbances are distributed within the magnetosphere, and how torque variability is related to bright X-ray outbursts.

6. FUTURE SCIENCE AND REQUIREMENTS

The Square Kilometre Array (see the white paper by Taylor) is essential to accomplish the radio science – timing, astrometry and deep imaging – described above. In fact, GR tests with pulsars and black holes form one of the Key Science Projects for the SKA, and Canadian scientists are well-poised to take leading roles in the science collaboration, in part via work on pathfinder telescope pulsar science. CHIME (see the white paper by Pen et al.) is potentially of use for regular monitoring of pulsars at low frequencies, which would allow improved timing by millisecond pulsar timing arrays via better understanding of interstellar medium variations. It may also prove useful for searches for pulsars and RRATs.

In the X-ray domain, there is a rich diversity of new missions being built (Astrosat, NuSTAR, Astro-H, GEMS) and proposed missions (IXO, AXTAR, EXIST, WXFT). (See the white paper by Gallo et al.) Although there is already Canadian involvement in Astrosat, the timing of emerging missions will be determined externally. IXO represents a grand opportunity, but one with a potentially long timescale and definitely a large total cost. Complementary types of X-ray science can be accomplished with sensitive spectroscopy (NuSTAR, Astro-H, IXO), all-sky monitoring (EXIST or WXFT), deep pulsed source monitoring (AXTAR) and polarimetry (GEMS, followed by IXO).

Deep monitoring of pulsed X-ray sources (AXTAR) provides a very promising new avenue for pulsar searches – especially in the Galactic center region where radio pulses are strongly dispersed, and radio detections require the high-frequency sensitivity that can only be provided by the SKA. EXIST's deep survey for soft X-ray point sources would greatly broaden the sample of NSs that could be monitored for X-ray variability, a strategy that has already been pursued so successfully by Canadians with RXTE. Magnetars, DINS and strong-field radio pulsars all show transient behavior (in the case of magnetars, in practically every waveband), and much is still to be learned about the observational imprint of superfluid dynamics and magnetic field decay.

IXO will provide vastly improved sensitivity to spectroscopic features, with important implications for surface composition and magnetic field strength. NuSTAR and Astro-H will significantly improve our understanding of the hard X-ray emission of magnetars, which dominates their bolometric output. All-sky monitoring in the hard X-ray band with EXIST or WXFT would provide excellent prospects for widening the class of NSs which produce magnetar-type burst phenomena.

Sensitive, pointed hard X-ray missions such as NuSTAR and Astro-H are essential for fleshing out the sample of young galactic SNRs and PWNe, and measuring the Galactic supernova rate. They will also provide broader constraints on electron acceleration in SNR, as will new generations of TeV telescopes for ion acceleration. High-resolution X-ray spectroscopy by Astro-H in the 3-10 keV band will probe a wider range of nucleosynthetic products in supernova explosions. Measurements of X-ray polarization with IXO or GEMS are essential for developing detailed global models of pulsar wind circuits and SNR magnetic fields, and probing the magnetospheres of magnetars and middle-aged radio pulsars.

An overarching theme is that high-performance computing is essential to manage the enormous data throughputs associated with SKA, pulsar searches, and all-sky monitoring, as well as to enable theoretical modeling. Canada's existing strength in this area needs to be maintained and reinforced.

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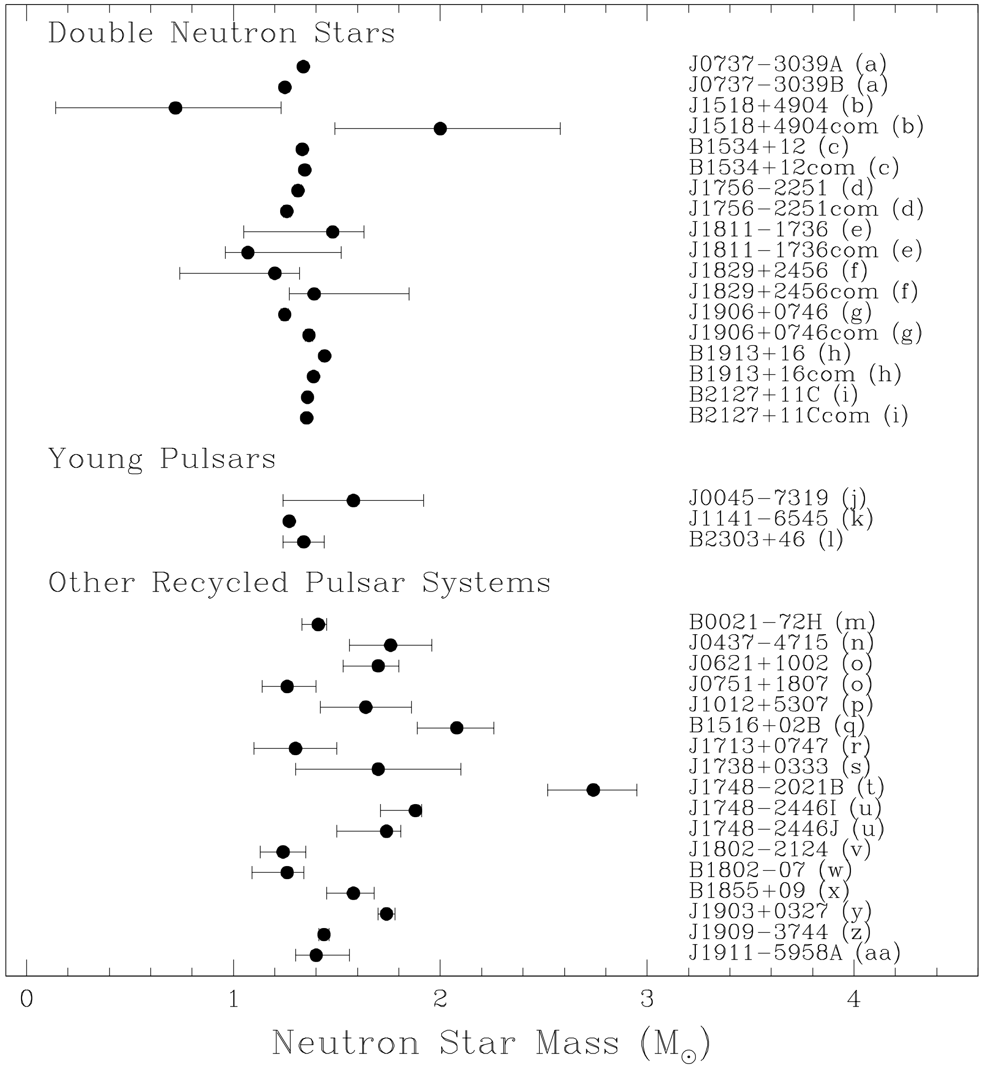

FIG. 1.— Masses of radio pulsars in binary systems, grouped by binary type, although the pulsars in the last group have a wide range of companion types. Most measurements result from determination of relativistic timing parameters, although optical spectroscopy of companions contributes in some cases. Not all measurements are equally robust: in particular, the indicated masses for the J1811–1736, J1829+2456, B0021–72H, B1516+02B, J1748–2021B and J1748–2246I and J systems rely entirely on the dual assumptions that the measured advance of periastron is purely due to general relativity, and that the orbit is likely to be randomly oriented, following the method outlined in Thorsett & Chakrabarty (1999) for J1518+4904. References: (a) Kramer et al. (2006) (b) Janssen et al. (2008) (c) Stairs et al. (2002) (d) Ferdman (2008) (e) Corongiu et al. (2007) (f) Champion et al. (2005) (g) Kasian (2008) (h) Weisberg & Taylor (2003) (i) Jacoby et al. (2006) (j) Bell et al. (1995) (k) Bhat et al. (2008) (l) van Kerkwijk & Kulkarni (1999) (m) Freire et al. (2003) (n) Verbiest et al. (2008) (o) Nice et al. (2008) (p) Callanan et al. (1998) (q) Freire et al. (2008c) (r) Splaver et al. (2005) (s) Freire et al. (2008a) (t) Freire et al. (2008b) (u) Ransom et al. (2005) (v) Ferdman et al. (2010) (w) Thorsett & Chakrabarty (1999) (x) Splaver (2004) (y) **Champion** et al. (2008) (z) Jacoby et al. (2005) (aa) Bassa et al. (2006)

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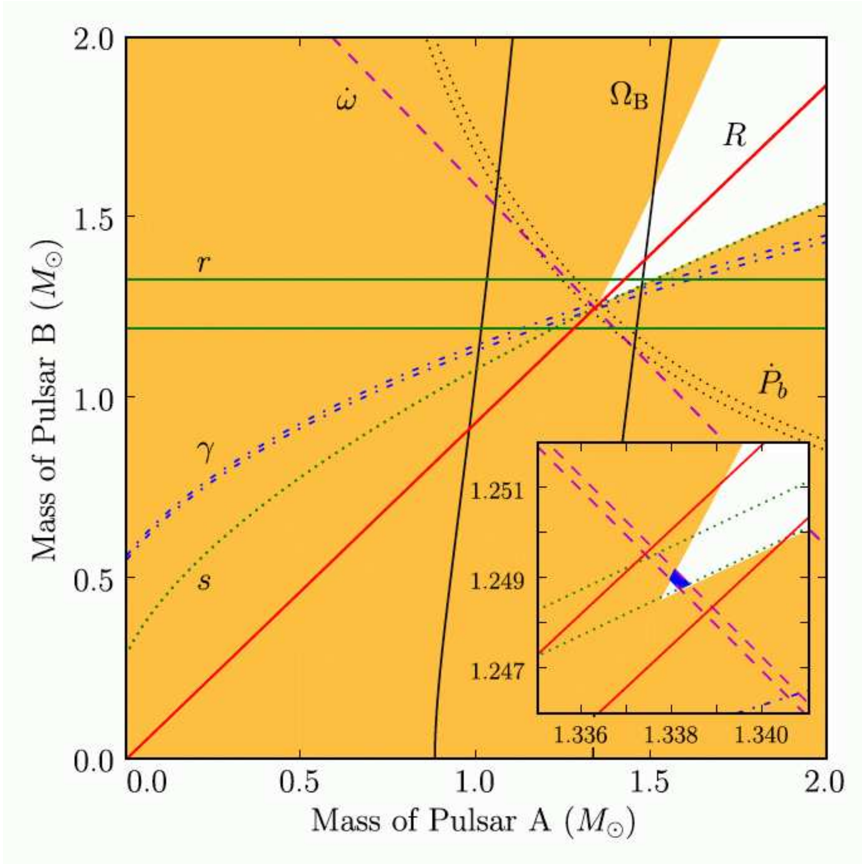

FIG. 2.— Bounds on binary parameters in the double pulsar system PSR J0737−3039A/B from radio timing of the faster pulsar A. Here $\dot{\omega}$ is the rate of periastron advance, $\dot{P}_b$ the decrease of the binary period due to gravity wave emission, γ the gravitational redshift and time dilation parameter, and r,s the range and shape parameters of the Shapiro time delay that radio signals experience propagating through the binary gravitational field. The pulsar mass ratio R is accurately measured in this system due to its well-determined inclination. Also measured is the rate of spin precession Ω_B of pulsar B, via changes in the eclipse that its magnetosphere induces in the radio flux from A. From **Breton** et al. (2008).

FIG. 3.— X-ray shell of SNR G21.5-0.9 revealed by Chandra, surrounding an extended synchrotron nebula that is emitted by PSR J1833-1034. Image Credit: NASA/CXC/U. Manitoba/H. Matheson & S. Safi-Harb.

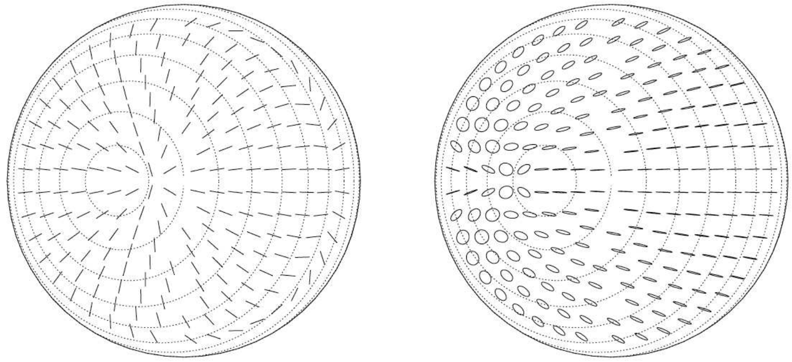

FIG. 4.— Polarization pattern of the X-rays emerging from the magnetosphere of a thermally emitting neutron star with a strong dipolar magnetic field (Heyl & Shaviv 2002). Left panel: linearly polarized emission neglecting the effects of vacuum birefringence; right panel: including the effects of birefringence and polarization mode tracking through the varying magnetic field.

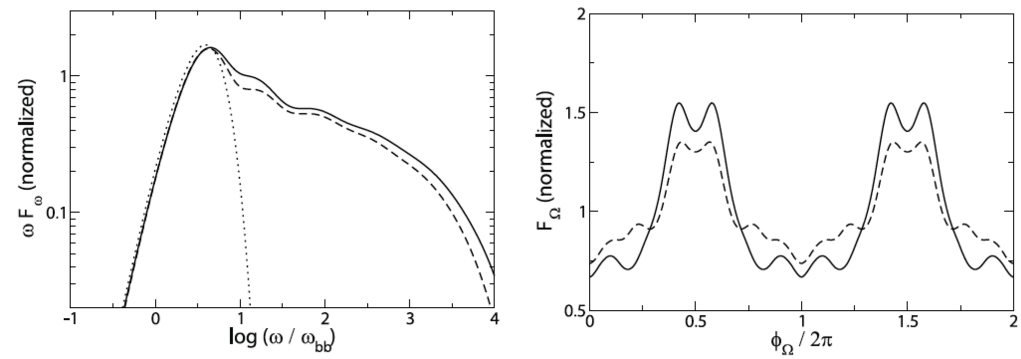

FIG. 5.— Shearing of a neutron star magnetic field has a strong measurable effect on the emergent X-ray spectrum and pulse profiles. Result of Monte Carlo calculation of frequency and angle redistribution from **Fernández** & **Thompson** (2007). The charges that supply the electric current induce an optical depth O(1) to resonant cyclotron scattering over a continuous range of frequencies below the surface cyclotron frequency.

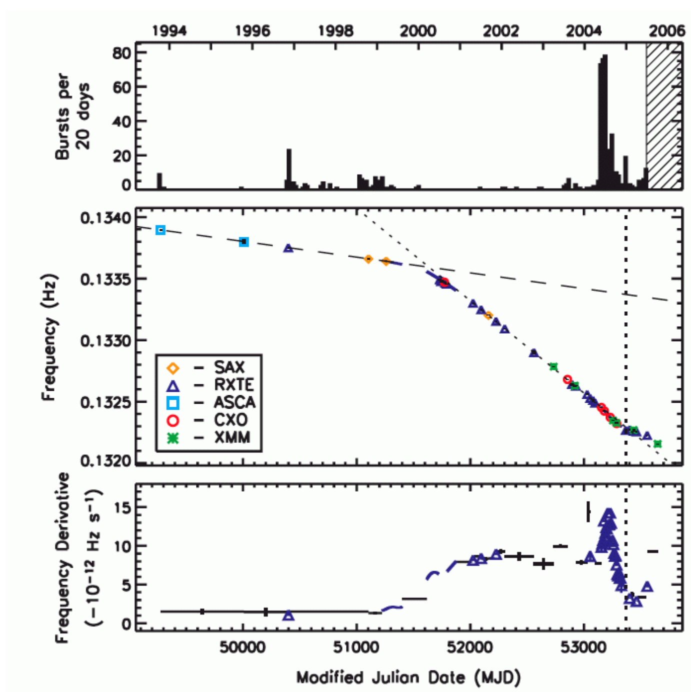

FIG. 6.— Remarkable torque variability measured in the magnetar SGR 1806-20, the source of the most extreme magnetar flare yet detected (on 2004 December 26). Phase connected timing of RXTE data, using the technique pioneered by Kaspi and collaborators for magnetars. Strong non-thermal X-ray emission and torque variability are present even during periods of burst quiescence. From Woods et al. (2007).

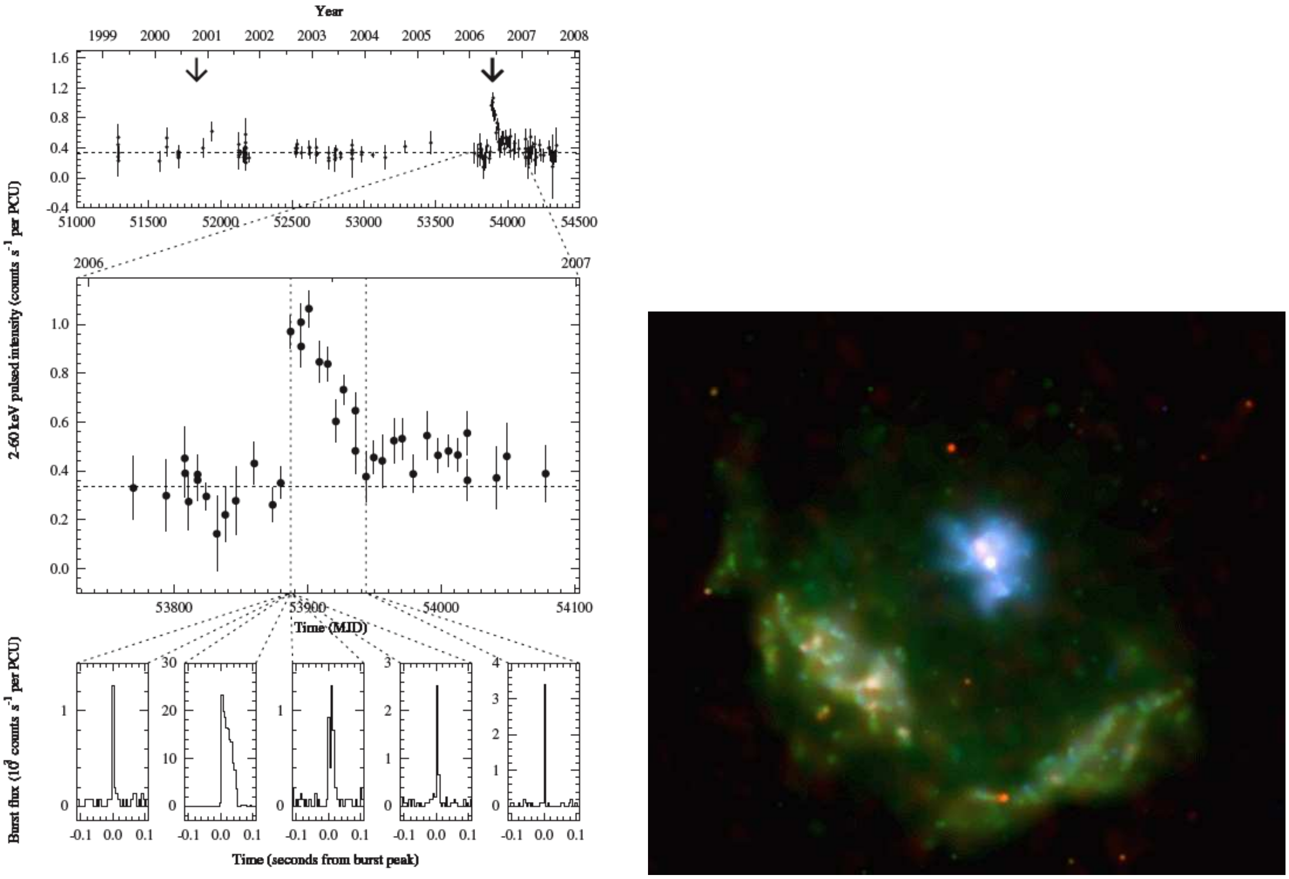

FIG. 7.— Discovery of magnetar-like X-ray activity in the rotation-powered pulsar in Kes 75. The polar magnetic field estimated from spindown is 5×10^{13} G, just below the magnetar range. Activity plot (left) from Gavriil et al. (2008), PWN+SNR map (right) from **Kumar** & **Safi-Harb** (2008).

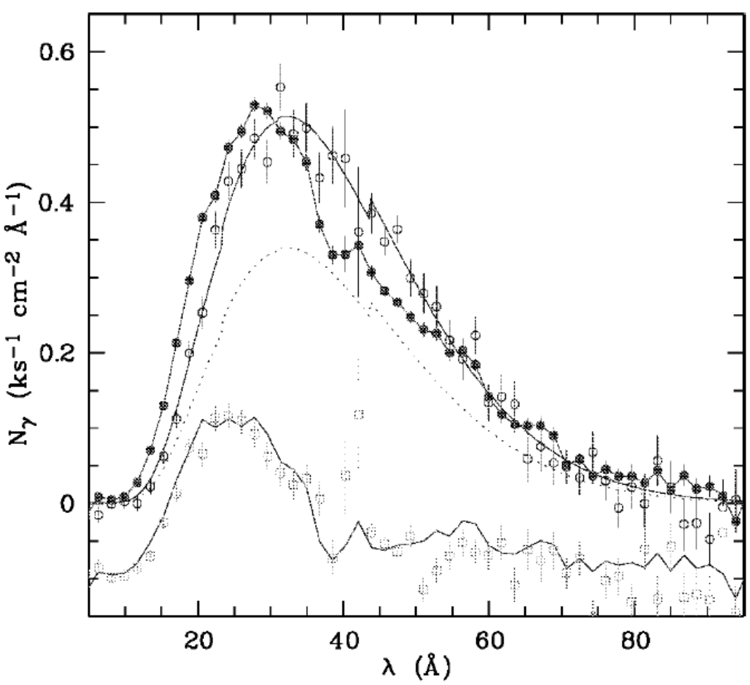

FIG. 8.— Variability in the X-ray spectrum of the thermally emitting NS RX J0720.4-3125, possibly due to a change in surface composition. The emergence of an absorption line feature was not accompanied by a measureable change in bolometric X-ray output. From **van Kerkwijk** et al. (2007).